The aim of this document is twofold. It first details how to transform the CT and blueprint based patient data to data that are readable for the shoulder and elbow musculoskeletal model (MSM). It then describes how to transform the MSM predictions (output data) to data readable for the shoulder simulator test setup from LMAM.

It is assumed that the reader is familiar with the MSM. Otherwise, it is recommended to follow the readme file of the MSM to obtain an overview of the MSM (smb://lbovenus/shoulder/methods/matlab/MSM/ShoulderModel/README.txt).

From CT/Blueprint to MSM inputs:
The Subject-specific sub-tool of the MSM takes as inputs the following data in order to adapt the generic model to each specific subject:

- Gender
- Weight [kg]
- Height [m]
- Muscle PCSA [cm^2]
- Glenoid orientation, including:
    - Glenoid version [degree]
    - Glenoid inclination [degree]
    - Glenoid fossa center in the scapula coordinate system[1] (^{S}GC) [mm]
    - Implant/humeral head diameter (Implant diameter for total shoulder arthroplasty patients and humeral head diameter for healthy subjects) [mm]

The first three inputs of the list (gender, weight, and height) and the implant diameter can be readily obtained from an excel file including the patient data. It is located in lbovenus/shoulder/data/Excel/ShoulderDataBaseDev.xlsx. In this document we will refer to this file as shoulder data base.

Muscle PCSA:
In the MSM, muscle PCSAs are scaled for each patient according to the gender, weight, and height. However, the user can fancy adapting the values to measured patient-specific values.
From the Shoulder data base, the user can obtain a relative PCSA percentage ($PCSA_r$) for the four rotator cuff muscles of each patient. The $PCSA_r$ is a measure of the remaining muscle cross section area with respect to its healthy situations. The PCSA that the MSM can take in absolute sense ($PCSA_a$) is obtained as the following:

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[1] The scapular coordinate system is defined according to "Terrier, A., et al. "Measurements of three-dimensional glenoid erosion when planning the prosthetic replacement of osteoarthritic shoulders." The bone & joint journal 96.4 (2014): 513-518." and is detailed in the Appendix. Note that this scapula coordinate is defined differently than the scapula coordinate system of the MSM that is defined according to ISB recommendations and used for defining the configuration of the scapula with respect to thorax.

$$PCSA_a = (1 - PCSA_r) * PCSA_s \qquad (1)$$

Where, $PCSA_s$ is the scaled value from the MSM. In other words, first scale the model through the subject-specific tool, then for each one of the rotator cuff muscles adapt the PCSA using the Eq. 1.

For instance, the adaptation of PCSA of Supraspinatus is shown for P281 in Fig. 1.
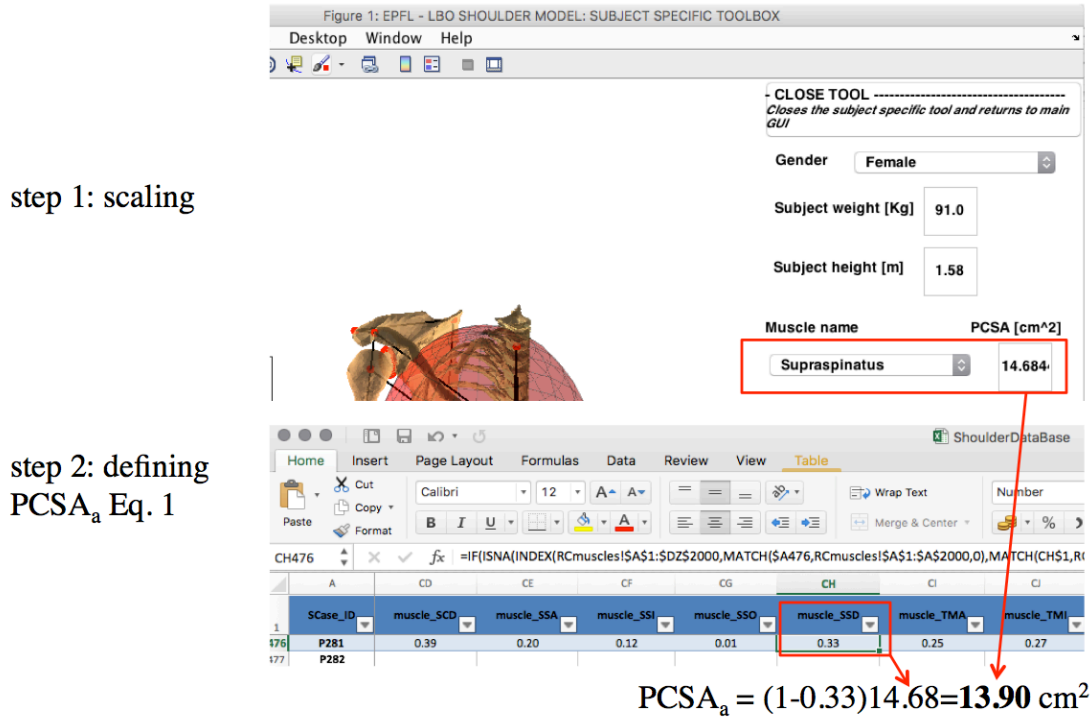

Fig. 1: adaptation of PCSA of Supraspinatus

Glenoid orientation:

Glenoid orientation has an important impact on the MSM predictions. It defines the configuration of the stability cone and also affects the insertion/origin and wrapping of the muscles as well as the bony landmarks proximal to the glenohumeral joint. By providing the abovementioned four inputs (Glenoid version, inclination, ^{S}GC and implant/humeral head diameter) the MSM defines a patient-specific glenohumeral joint center in thorax frame (^{T}GH) (Fig. 2). Having defined, the patient-specific ^{T}GH, the MSM finds a shift value by subtracting the patient-specific ^{T}GH from the scaled ^{T}GH obtained by only scaling the generic model according to the patient height. All the bony landmarks and muscle insertion/origins and wrapping objects proximal to the GH joint are then displaced with the amount of the shift value.
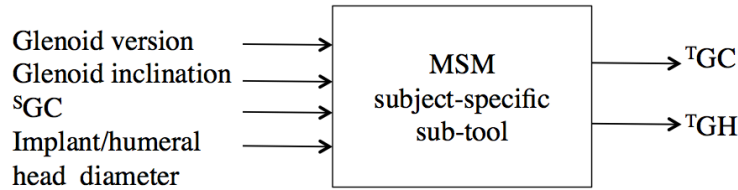
Fig. 2: Glenoid orientation data is used to define a patient-specific ^{T}GH

Implant/humeral head diameter can be obtained from either the shoulder data base or patients' blueprint data. Blueprint is the software that allows performing the preoperative planning. Blueprint reports for each patient can be obtained from lbovenus/shoulder/data/P/… . For instance, for P281: lbovenus/shoulder/data/P/2/8/ P281-127547/CT-P281-127547-1[1]/blueprint/P281-blueprint.txt

Although there are values available for glenoid version and inclination in the shoulder data base, these values are not obtained using consistent definitions as of the MSM's. Therefore, the following steps are to follow to obtain consistent values for the MSM.

Step 1: Obtain the scapula coordinate system for each patient. To this end, first set the directory of MATLAB to lbovenus/shoulder/methods/matlab/database. Then in the Command Window use `PlotSCase('PXXX')`command where XXX is the patient's identifier, e.g. `PlotSCase('P281')`. This provides a structure within which you can find x, y, and z axes of the scapula coordinate system as well as the scapula notch in the CT coordinate system (^{CT}SN) (Fig. 3).

Step 2: Explore to folder containing the patient's blueprint data as explained before, and take the following fields:
- GlenoidImplant_LateralAxis
- GlenoidImplant_Center

GlenoidImplant_LateralAxis is the normal vector of the glenoid implant surface in the lateral direction and in the CT coordinate system (^{CT}GC$_{axis}$). GlenoidImplant_Center is associated to the center of the glenoid implant in the CT coordinate system (^{CT}GC). To obtain ^{CT}GC, you must add GlenoidImplant_Center to the image position in CT. The image position in the CT can be obtained either by loading all the patient's CT data in AMIRA or loading the most inferior CT in MATLAB using "dicominfo" command. For instance for P281:

```
allfields = dicominfo('/Volumes/shoulder/data/P/2/8/P281-127547/CT-
P281-127547-1/dicom/P281-127547_JN-bone.0001.dcm');
```


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[1] Always the folder that ends in "-1"

Step 3: Having obtained the abovementioned data in Step 1 and Step 2, you can define the glenoid version, inclination, and center in scapula coordinate system as the following.

1) Define the rotation matrix from scapula coordinate system to the CT coordinate system: $^{CT}_{S}R = [x \quad y \quad z]$, where x, y, and z are scapula coordinate system axis obtained in Step 1.

2) Define $^{S}GC_{axis} = {}^{CT}_{S}R'{}^{CT}GC_{axis}$.

3) Define glenoid version and inclination angles:

$$\text{Glenoid\_version} = \text{atand}\left(\frac{^{S}GC_{axis}(1)}{^{S}GC_{axis}(3)}\right)$$

$$\text{Glenoid\_inclination} = \text{atand}\left(\frac{^{S}GC_{axis}(2)}{^{S}GC_{axis}(3)}\right)$$

4) Define the ^{S}GC:

$$^{S}GC = {}^{CT}_{S}R'\left({}^{CT}GC - {}^{CT}SN\right) + [0 \quad 0 \quad d]'$$

Where, d is a constant associated with the thickness of the glenoid implant component and is usually equal to 4 [mm].
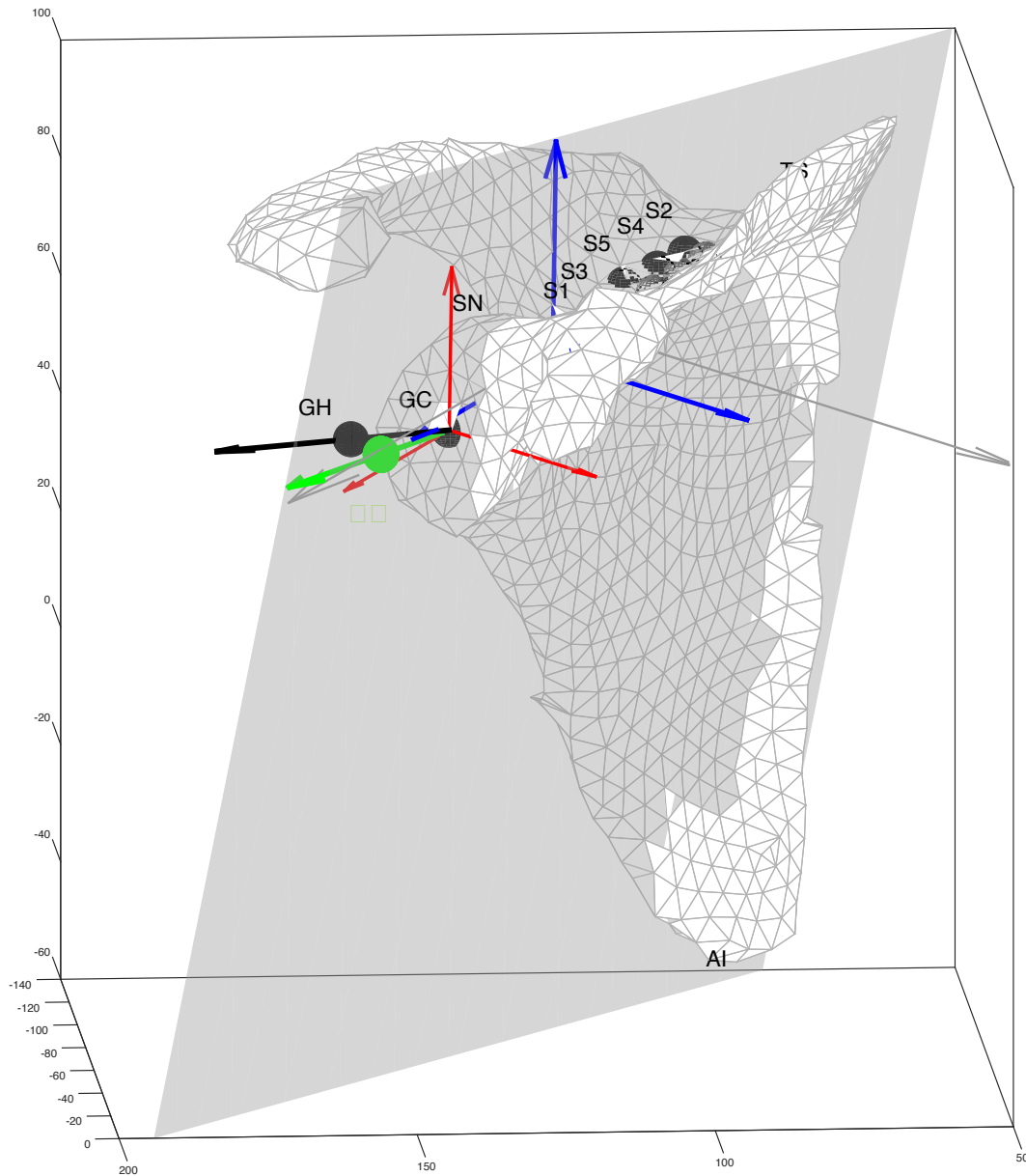
Fig. 3: Illustration of the scapula coordinate system and construction of a subject-specific GH landmark. The scapula coordinate system is shown in blue. The gray plane is the scapula plane. The red coordinate system is a coordinate system that is constructed by translating the scapula coordinate system from the projection of SN on the scapula plane to the GC point. The green vector is the normal vector of the glenoid implant (GC_{axis}). The black vector is GC_{axis} but for the generic model. Using the subject specific GC_{axis} (the green vector) a subject specific GH landmark is defined (the green GH point).

Provided all the inputs, the MSM can construct ^{T}GC and the subject-specific ^{T}GH using the GH_{axis} and the implant/humeral head diameter. This is done in the subject-specific sub-toolbox of the MSM.

The abovementioned steps were coded for 20 SOGI patients in "glenoid_orientation_preparation.m".

From MSM to shoulder simulator:

All the necessary steps required for transforming the MSM outputs to readable inputs for the shoulder simulator were already implemented in the MSM. The only point that was brought up lately was the necessity of defining a coordinate system for the humeral head implant. In other words, the MSM provides the glenohumeral joint reaction force in the thorax frame. However, the shoulder simulator requires the force in the humerus implant coordinate. Therefore, the aim of this section is to define a coordinate system for the humerus implant and to provide its corresponding rotation matrices. In addition[1], the shoulder simulator requires the kinematics from the glenoid implant to the humerus implant. To this end, it is also necessary to define the humerus implant. Equation (2) shows how to define the kinematics from the glenoid implant to the humerus implant.

$$\underset{GI}{\overset{HI}{R}} = \underset{H}{\overset{HI}{R}} \ \underset{T}{\overset{H}{R}} \ \underbrace{\underset{S}{\overset{T}{R}} \ \underset{T}{\overset{S}{R}_0} \underset{cone}{\overset{T}{R}_0} \underset{GI}{\overset{cone}{R}_0}}_{\underset{GI}{\overset{T}{R}}} \tag{2}$$

Where, $\underset{GI}{\overset{cone}{R}_0}$ is a rotation matrix from glenoid implant to the stability cone frame at the initial configuration (0 index) and it is defined as a rotation matrix around x axis with an angle (Θ) defined based on the positioning of the glenoid implant. In the current configuration of the shoulder simulator, it is tried to keep Θ equal to zero. $\underset{T}{\overset{S}{R}_0}$ and $\underset{cone}{\overset{T}{R}_0}$ are rotation matrices from thorax to scapula and from glenoid cone to thorax in the initial configuration, respectively. These two rotation matrices are available in the MSM outputs (for details check the MSM readme.txt). $\underset{H}{\overset{HI}{R}}$ and $\underset{T}{\overset{H}{R}}$ are rotation matrices from humeral to humerus implant and from thorax to humerus frame, respectively. The definition of the humerus implant coordinate system is detailed in the followings.

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[1] The shoulder simulator is an ongoing project that might face different changes during its developmenet. The definition of all possible coordinate system (e.g. for the humeral implant, glenoid implant, ...) helps to have the necessary information for any possible changes in the shoulder simulator project.
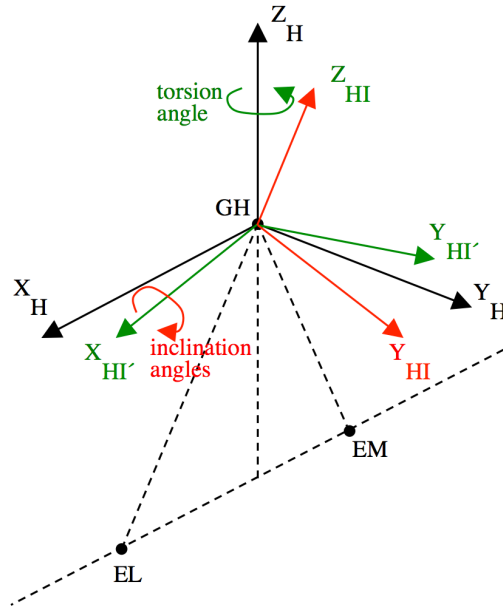
Fig. 4: Construction of the humerus implant coordinate system (red) from humeral coordinate system (black) through an intermediate coordinate system (green). EM and EL are two bonylandmarks on the the proximal end of the humerus used to construct the humeral coordinate system according to the ISB recommendations.

The humeral implant coordinate system can be obtained through two successive rotations from the humeral coordinate system. The two rotations are with two angles known as torsion (τ) and inclination (ι)[1]. Inclination is typically 132°. Note that in Eq (3) it should be considered as $\iota = -180° + 132°$.

$$
{}_{HI}^{H}R \;=\; \underbrace{\begin{bmatrix} \cos\tau & -\sin\tau & 0 \\ \sin\tau & \cos\tau & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{{}_{HI'}^{H}R} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\iota & -\sin\iota \\ 0 & \sin\iota & \cos\iota \end{bmatrix}}_{{}_{HI}^{HI'}R} \tag{3}
$$

Appendix (Scapula coordinate system):
This appendix details the construction of the scapula coordinate system used to define the glenoid orientation. As mentioned earlier, the scapula coordinate system used to define the glenoid orientation is different than the one that is used in the MSM to define the scapula configuration with respect to thorax according to ISB recommendations. The scapula coordinate system is constructed following the steps below using the bony landmarks shown on the next figure.

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[1] Krahl, Vernon E. "The phylogeny and ontogeny of humeral torsion." American journal of physical anthropology 45.3 (1976): 595-599.
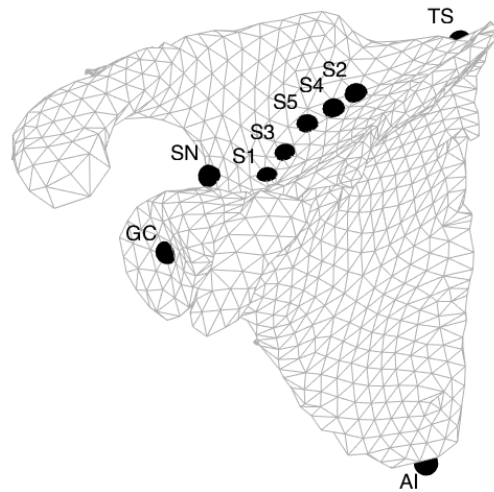
1. Define the scapula plane using the bony landmarks S1, TS, and AI, as shown in the next figure. Consider its normal vector in the posterior-anterior direction as the x direction axis of the scapula coordinate system.
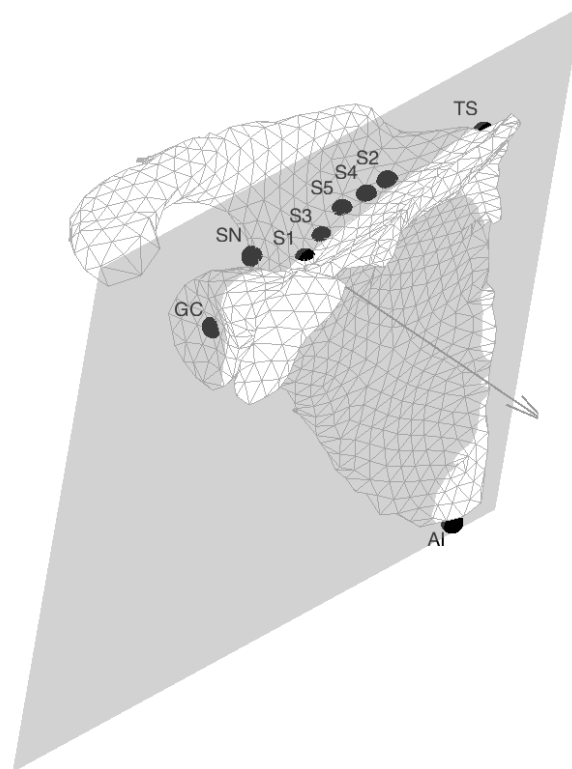

2. Project the five landmarks of the supraspinatus fossa (S1 to S5) and the scapula notch (SN) on the resulting scapula plane.
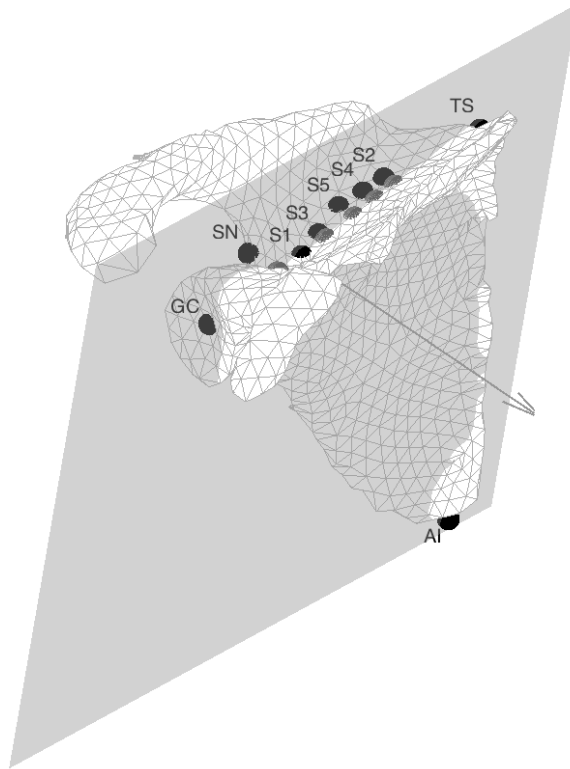
3. Fit a line through the resulting projected points and consider its medial-lateral direction as the direction of the z axis of the scapula coordinate system.
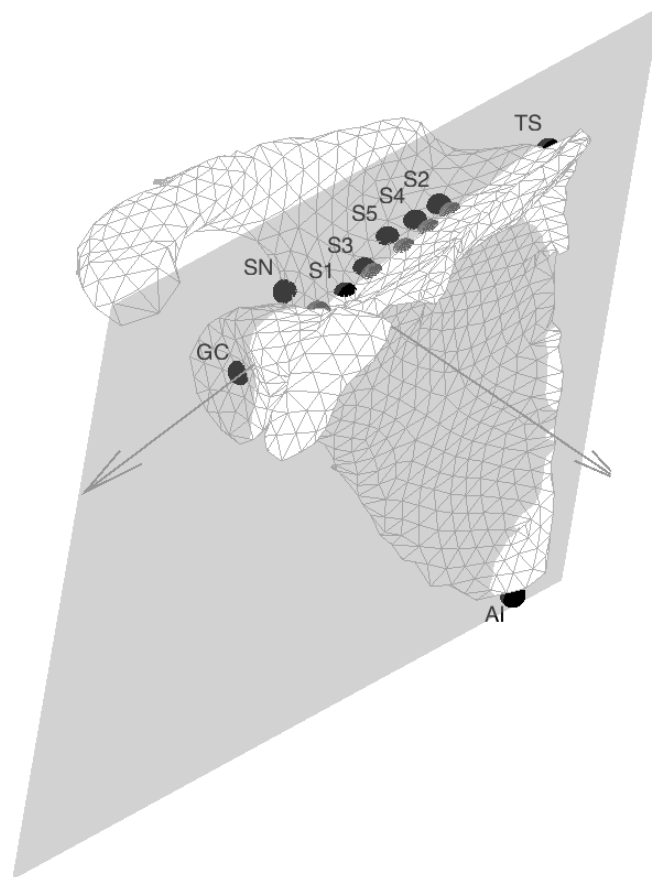
4. Construct a y axis by defining the common normal vector of the resulting x axis (step 3) and z axis (step 1) and construct the coordinate system on the project SN point.
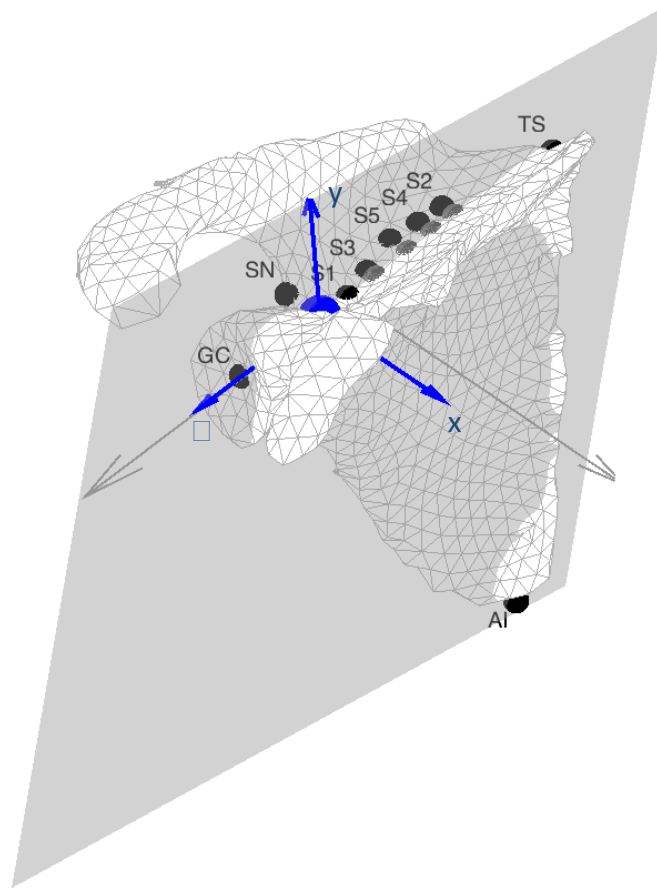
All the steps are coded in the "scapula_coordinate_system.m".